Quenching of heavy flavors at high p_T

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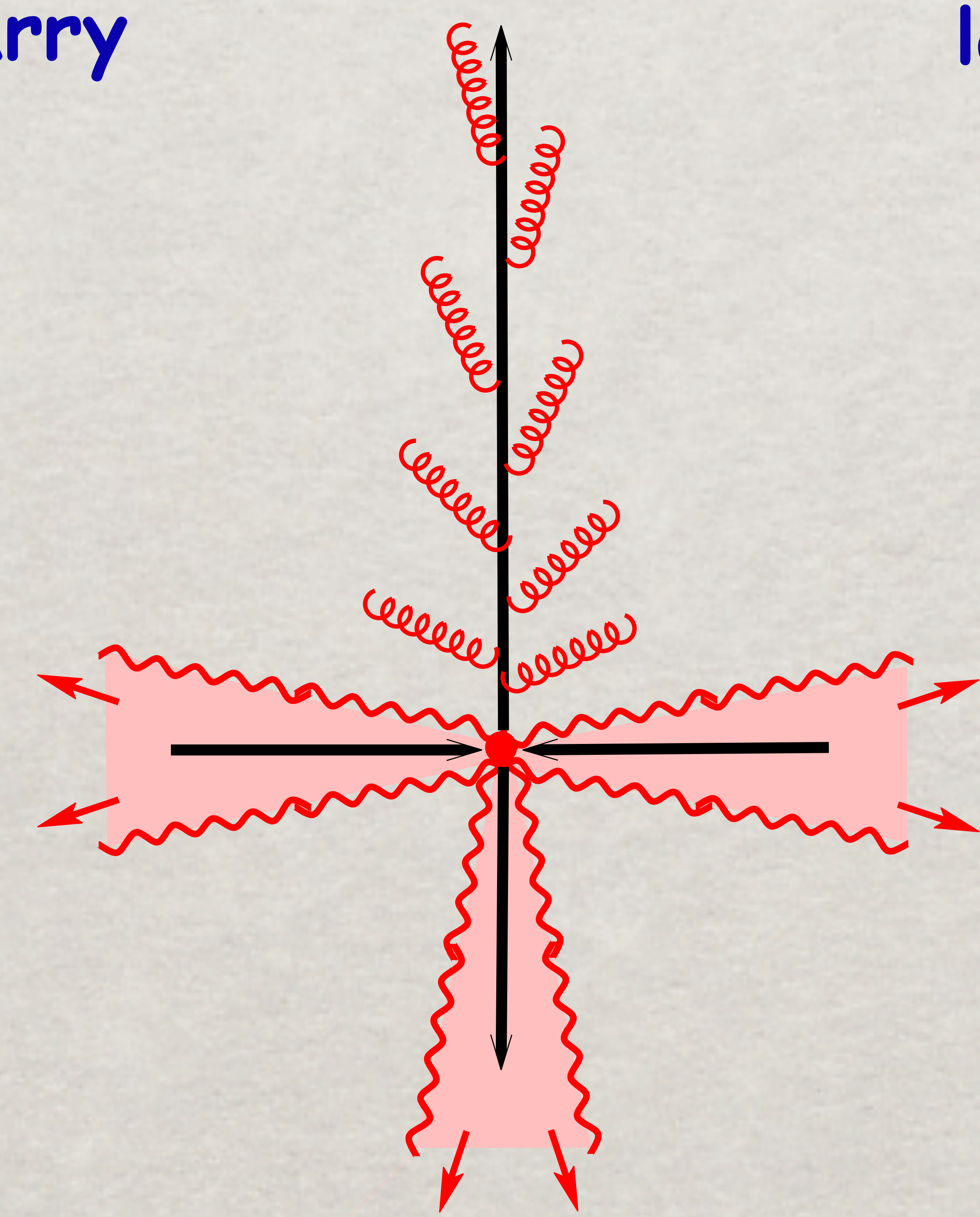
Hard parton collision

High-pt parton scattering leads to formation of 4 cones of gluon radiation:

(i) the color field of the colliding partons is shaken off in forward-backward directions.

(ii) the scattered partons carry no field up to transverse momenta kt<pT.

The final state partons are regenerating the lost color field by radiating gluons and forming the up-down jets.



The coherence length/time of gluon radiation

$$l_c = \frac{2E_q\, x(1-x)}{k_T^2 + x^2 m_q^2}$$

First are radiated, i.e. regenerated, gluons with small longitudinal and large transverse momenta.

A high-pT parton, whose color field was stripped off, cannot radiate extra gluons, unless the field is regenerated.

No medium-induced radiation is possible if the part of the field with corresponding values of x and kT has not been regenerated yet.

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B. Kopeliovich, BNL, April 12, 2016

Time dependent radiational energy loss in vacuum

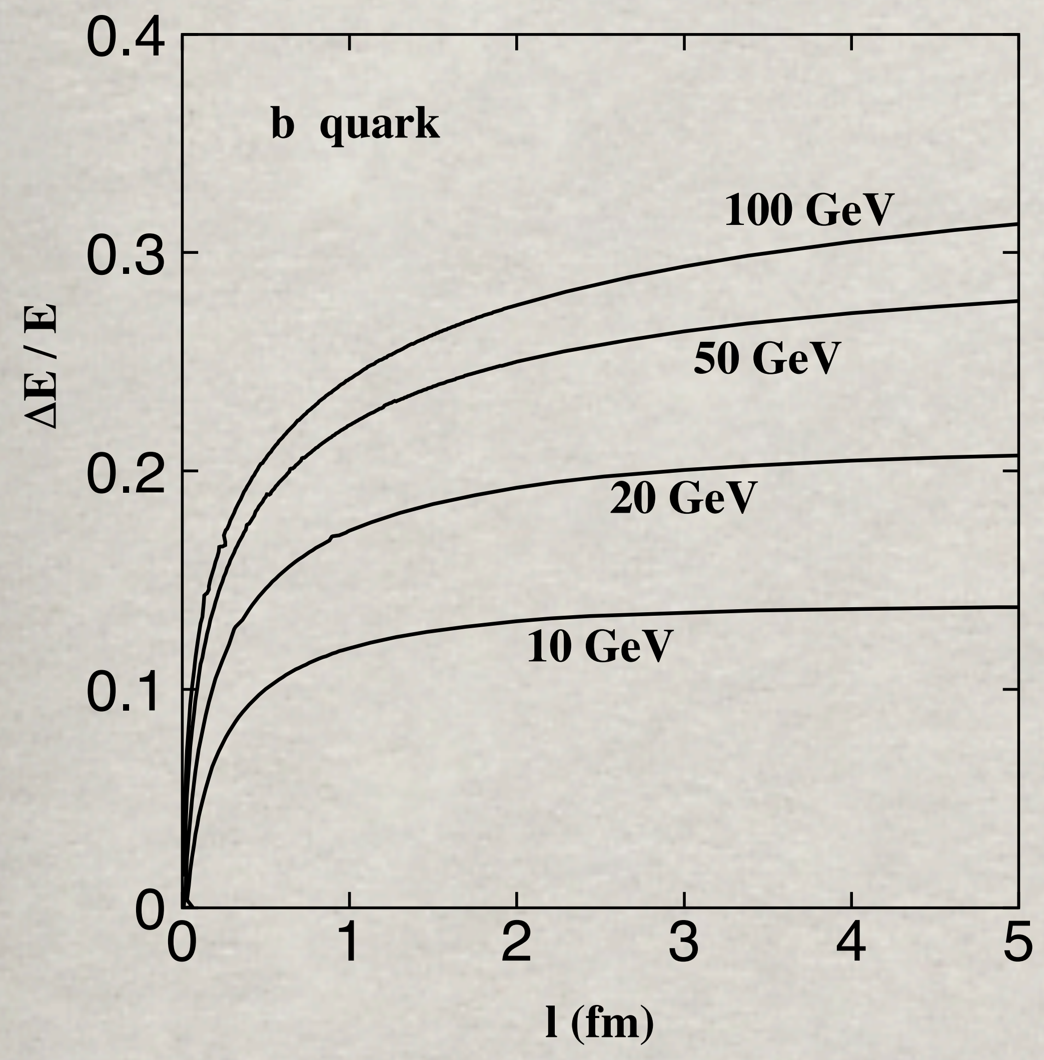
How much energy is radiated over path length l?

$$\Delta E(l) = E \int_{\Lambda^2}^{Q^2} dk^2 \int_0^1 dx\, x \frac{dn_g}{dx\, dk^2}\, \Theta(l - l_c)$$

$$\frac{dn_g}{dx\, dk^2} = \frac{2\alpha_s(k^2)}{3\pi x} \frac{k^2[1+(1-x)^2]}{[k^2 + x^2 m_q^2]^2}$$

Heavy quarks stop radiating earlier, and radiate much smaller fraction of the initial energy, compared with light quarks.

Dead-cone effect: gluons with $k^2 < x^2 m_q^2$ are suppressed.
Heavy quarks radiate less energy than the light ones.



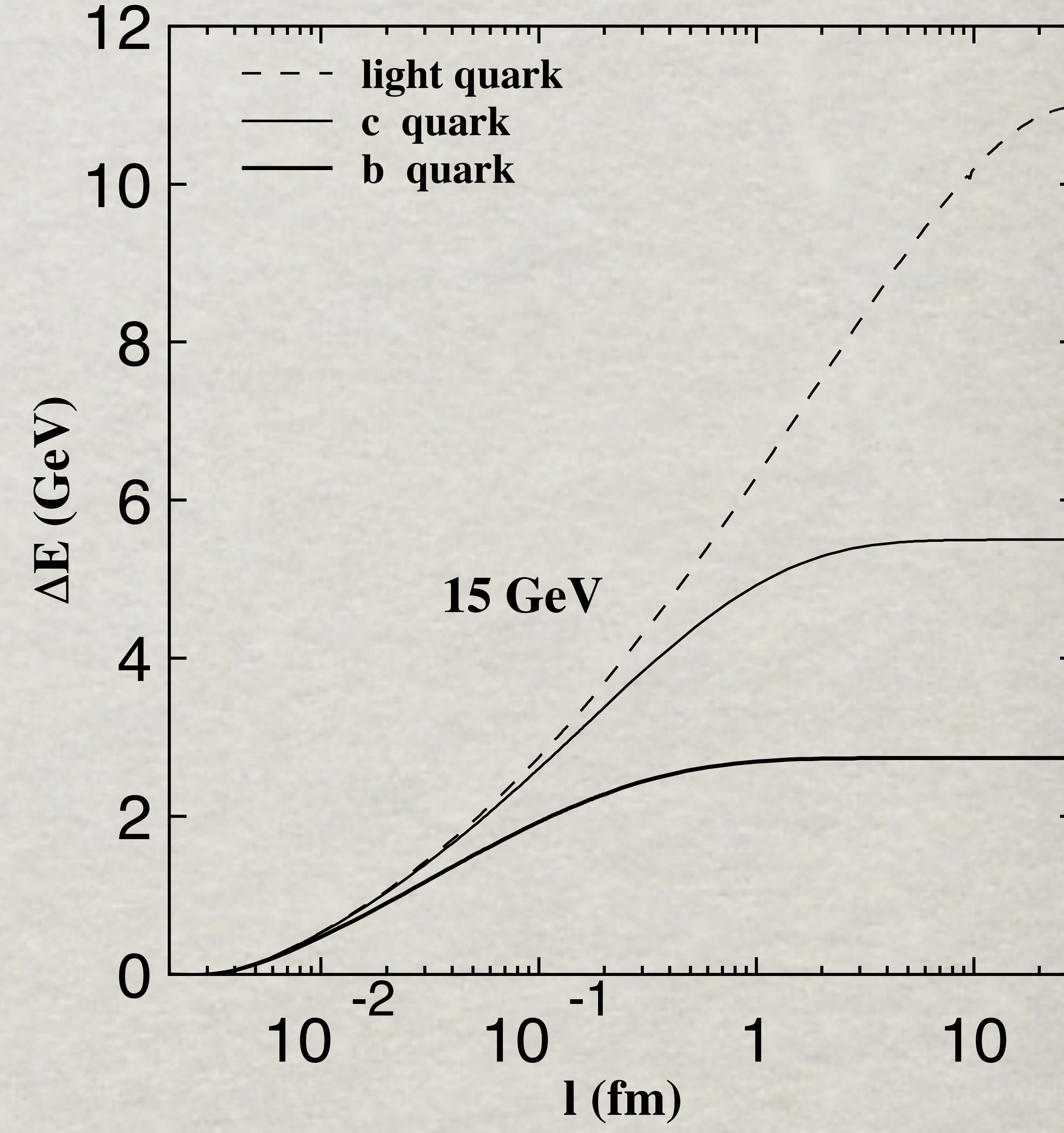
Another dead cone: medium-induced radiation is suppressed at a short path length

$$k^2 > \frac{2Ex(1-x)}{L} - x^2 m_q^2$$

because regeneration of the soft part of the stripped-off field takes long time

$$l_c = \frac{2E_q\, x(1-x)}{k_T^2 + x^2 m_q^2}$$

Thus, the radiation time effectively doubles.



I.Potashnikova,I.Schmidt & B.K.
PRC 82(2010)037901

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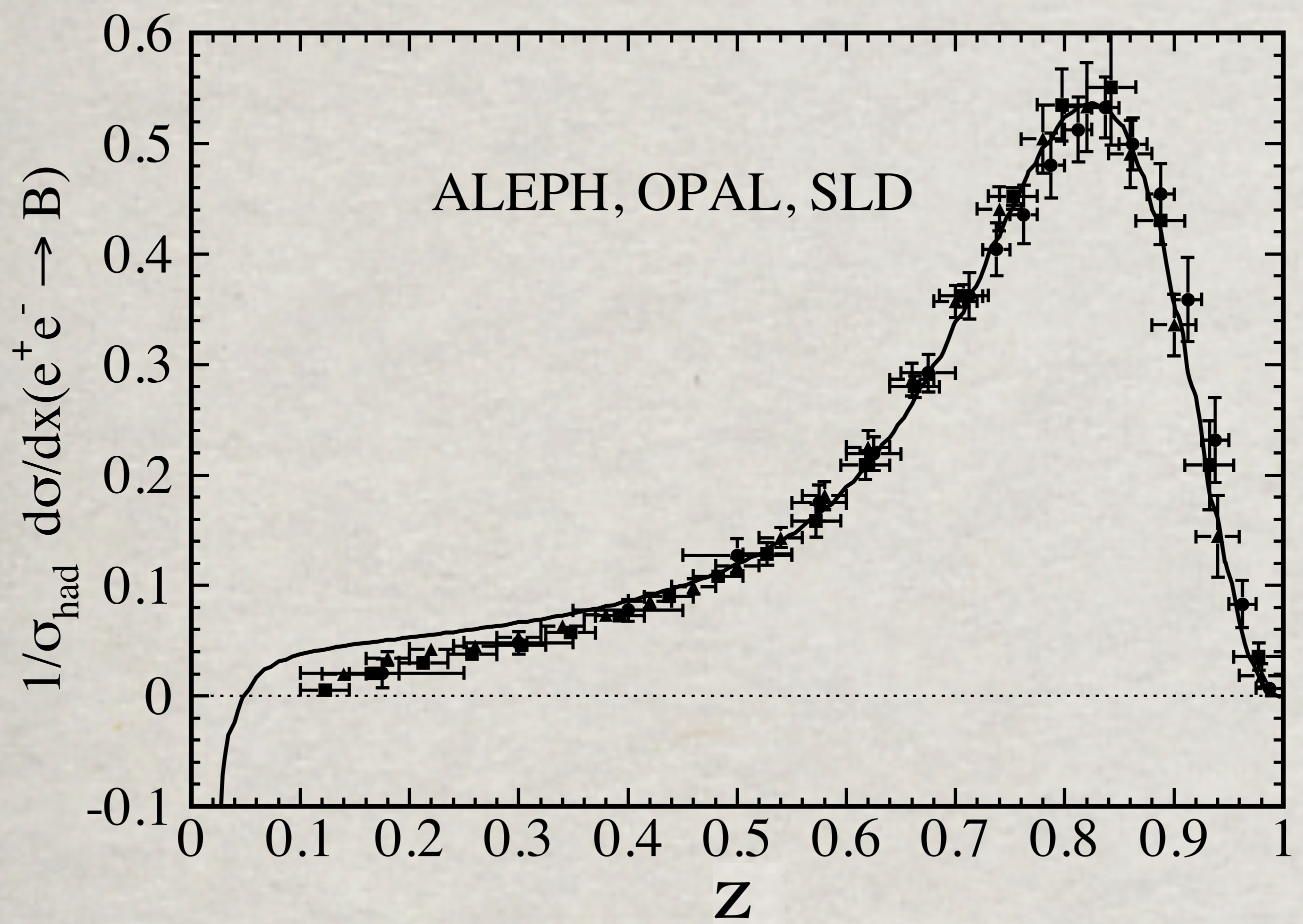
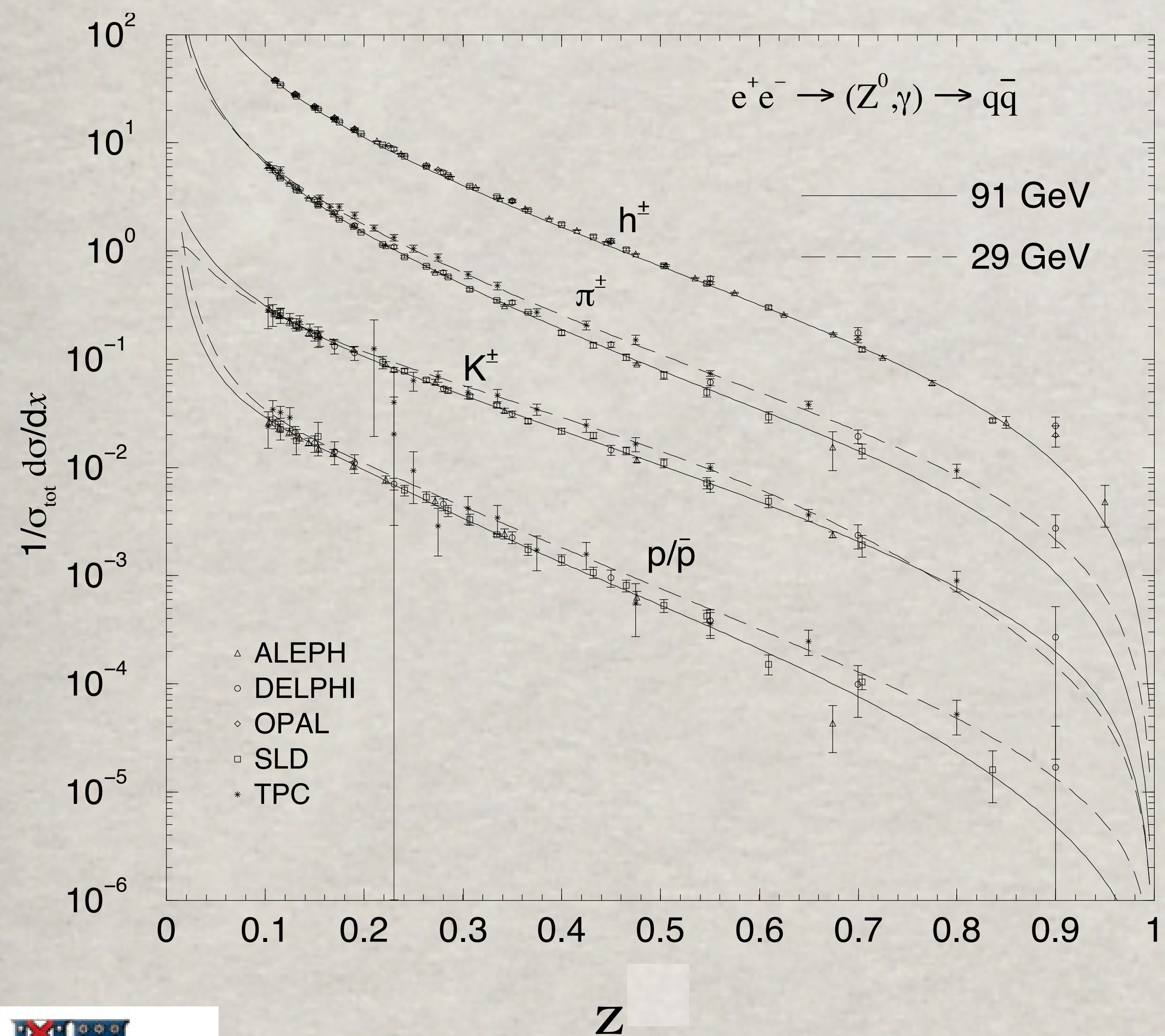
Fragmentation function of heavy quarks



Why small z are suppressed in the fragmentation of heavy flavors, but enhanced for light-quark jets?

The difference is in radiational energy loss in vacuum (previous slide). A heavy quark can radiate only a small fraction of its energy, Δz~ΔE/E.

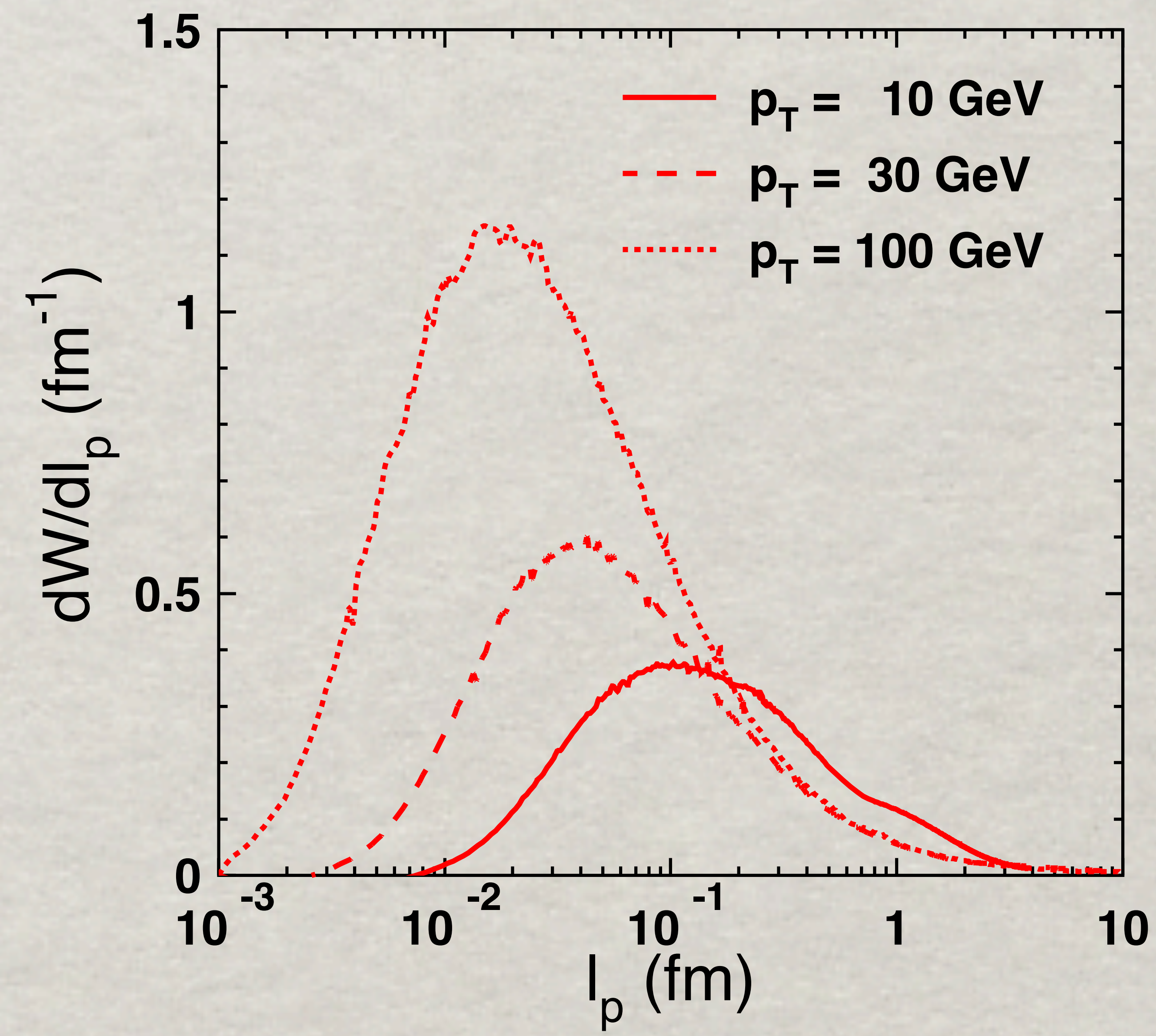
ΔE(l)/E is calculable, so the production length l_p of the B-meson can be extracted directly from $D_{b/B}(z)$



$$z \equiv \frac{p_+^B}{p_+^b} = 1 - \frac{\Delta p_+^b(l_p)}{p_+^b},$$

$$\Delta p_+^b(l_p) = \int_0^{l_p} dl\, \frac{dp_+^b(l)}{dl}$$

$$\frac{dW}{dl_p} = \frac{1}{p_+^b}\,\frac{\partial \Delta p_+^b}{\partial l}\bigg|_{l=l_p} D_{b/B}(z),$$



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Attenuation in a hot medium

The light quarks in the B-meson carries a tiny fraction of the momentum,

$\mathbf{x \sim m_q/m_b \approx 5\%}$

Therefore, even if the b-q dipole, produced at a short time scale, has a small transverse separation, its size expands with a high speed, enhanced by 1/x. The formation time of the B-meson wave function (in the medium rest frame) is very short,

$$\mathbf{t_f^B = \frac{\sqrt{p_T^2 + m_B^2}}{2m_B\omega}}$$

(ω=300MeV)

The mean free path of such a meson in a hot medium is even shorter

$$\mathbf{\lambda_B \sim \frac{1}{\hat{q}\,\langle r_T^2\rangle}}\,, \qquad \text{where} \quad \mathbf{\langle r_T^2\rangle = \frac{8}{3}\,\langle r_{ch}^2\rangle}$$

B meson is nearly as big as a pion, $\mathbf{\langle r_{ch}^2\rangle_B = 0.378\,fm^2}$ [Ch.-W. Hwang (2001)]

E.g. at $\mathbf{\hat{q} = 1\,GeV^2/fm}$ $\mathbf{\lambda_B = 0.04\,fm}$, i.e. the b-quark propagates through the hot medium, picking up and losing light quarks. Meanwhile the b-quark keeps losing energy with a rate, enhanced by medium-induced effects. Eventually the detected B-meson is formed and survives in the dilute medium at the surface.

Where the nuclear suppression comes from?

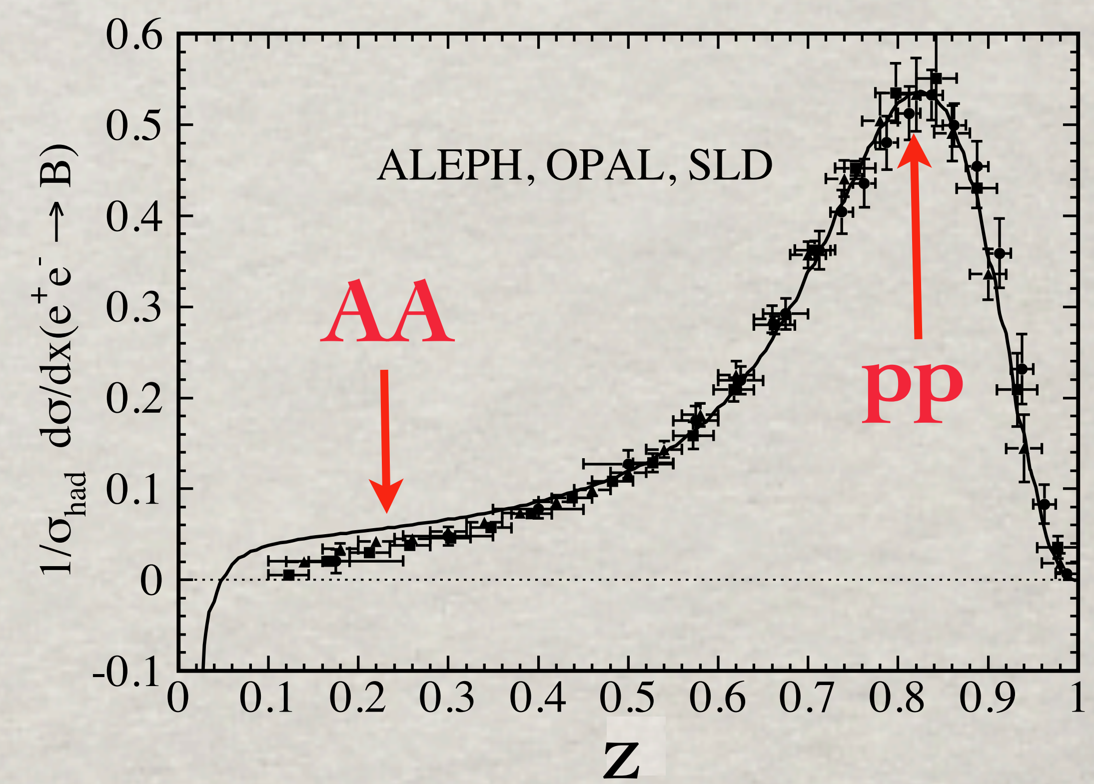
A high-pT b-quark, produced in pp collisions, starts radiating so intensely, that loses 20-30% of its initial energy on a very short distance, then picks-up a light antiquark. The produced colorless B-meson stops radiating and retains its fractional momentum z.

If, however, the b-quark is produced in a dense environment, it has to propagate a long distance until the medium surface, where the final B-meson can be produced. All this long path the quark keeps losing energy and eventually produces a B-meson with reduced fractional momentum z, which is suppressed by the fragmentation function.

$$\frac{d\sigma(pp \to BX)}{d^2p_T} = \int d^2p_T^b \, \frac{d\sigma(pp \to bX)}{d^2p_+^b} \, \frac{1}{z} D_{b/B}(z),$$

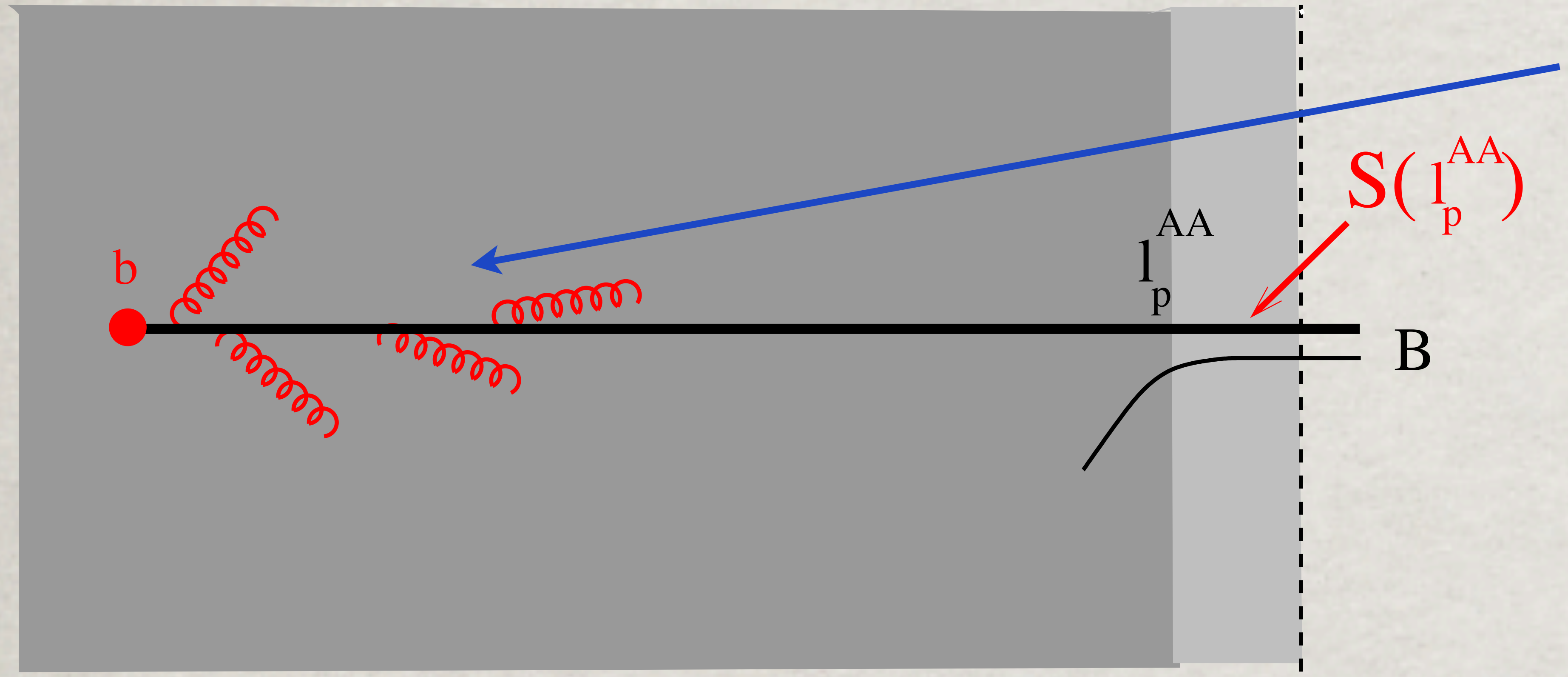
$$\frac{d\sigma(AA \to BX)}{d^2p_T} = \int d^2p_T^b \, \frac{d\sigma(pp \to bX)}{d^2p_T^b} \, \frac{1}{z_{AA}} D_{b/B}(z_{AA}) \, S(l_p^{AA})$$

$$S(l_p^{AA}) = \exp\left[-\frac{\langle r_B^2\rangle r_D^2}{2(\langle r_B^2\rangle + r_D^2)} \int\limits_{l_p^{AA}}^{\infty} dl \, \hat{q}(l)\right]$$



Debye screening radius provides a natural saturation scale for the dipole cross section

Interplay between energy loss & absorption



Energy loss in the medium: radiational vacuum and induced, collisional,string.

In vacuum: gluon radiation plus string

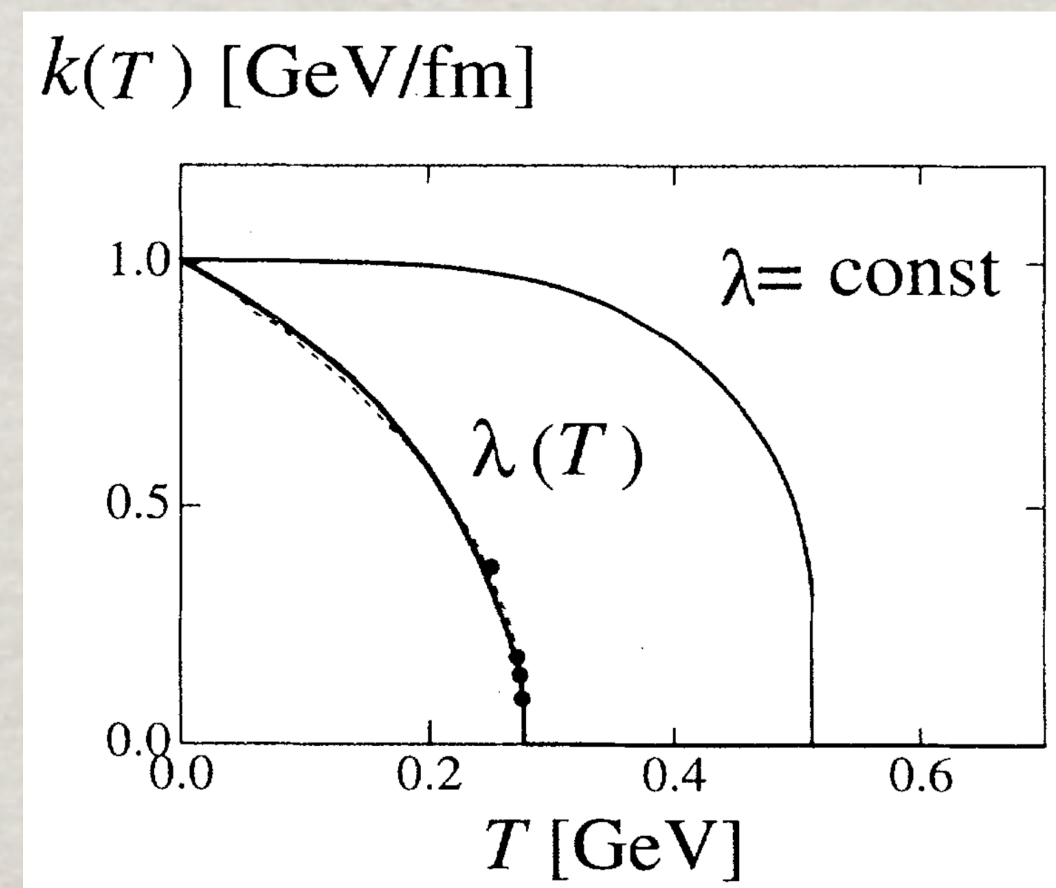
$$\mathbf{dE_{string}/dl = -\kappa \approx -1\,GeV/fm}$$

String tension is falling with temperature:

$$\kappa(T) = \kappa\,(1 - T/T_c)^{1/3}$$

While in vacuum a B-meson is produced on a very short length $\mathbf{l_p \ll 1\,fm}$, in a hot medium strong absorption pushes the production point to the dilute surface. However, energy loss on a longer $\mathbf{l_p}$ causes a large shift down to small z, suppressed by D(z).

Thus, the two sources of suppression are in conflict, leaving no good solution.



H.Ichie, H.Suganuma & H.Toki(1996)

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Results

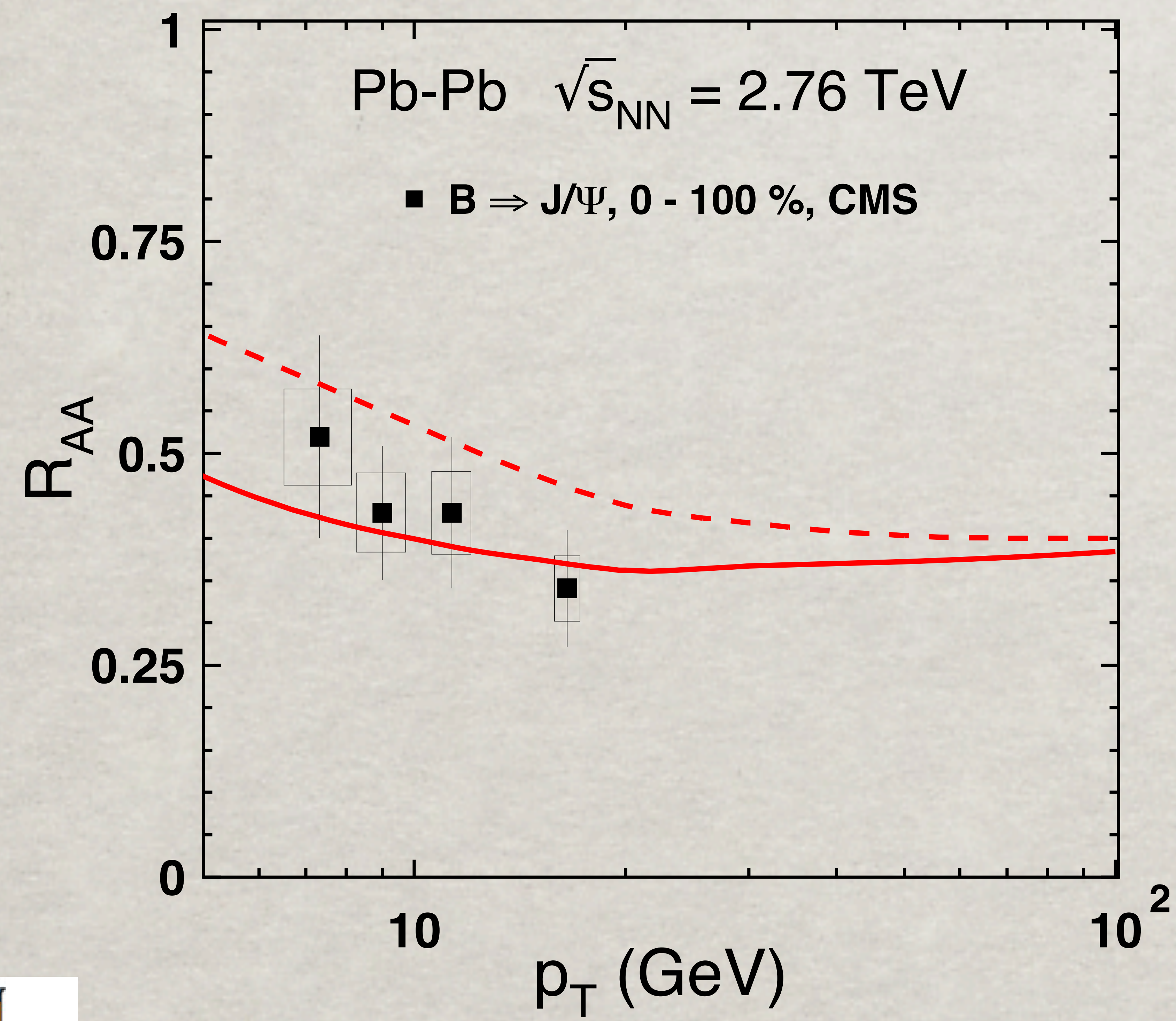
$$\hat{q}(l,\tilde{b},\tilde{\tau}) = \frac{\hat{q}_0\, l_0}{l}\,\frac{n_{part}(\tilde{b},\tilde{\tau})}{n_{part}(0,0)}\,\Theta(l-l_0),$$

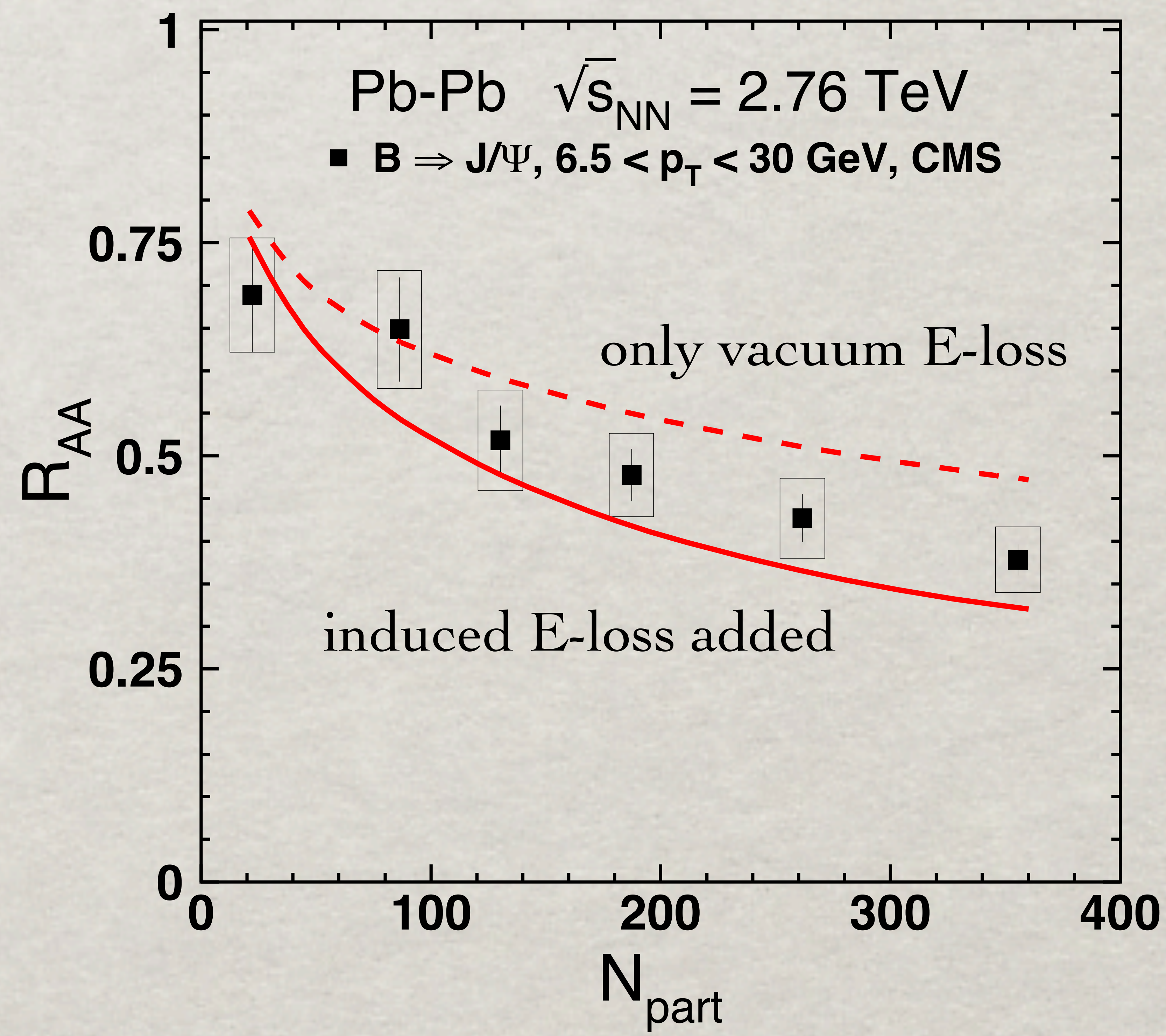
$$q_0 = 2\,\mathrm{GeV}^2/\mathrm{fm}$$
$$(1.6\,\mathrm{GeV}^2/\mathrm{fm})$$

fixed by quenching of pions at LHC (RHIC)

J.Nemchik,I.Potashnikova,I.Schmidt & B.K.
PRC 86(2012)054904

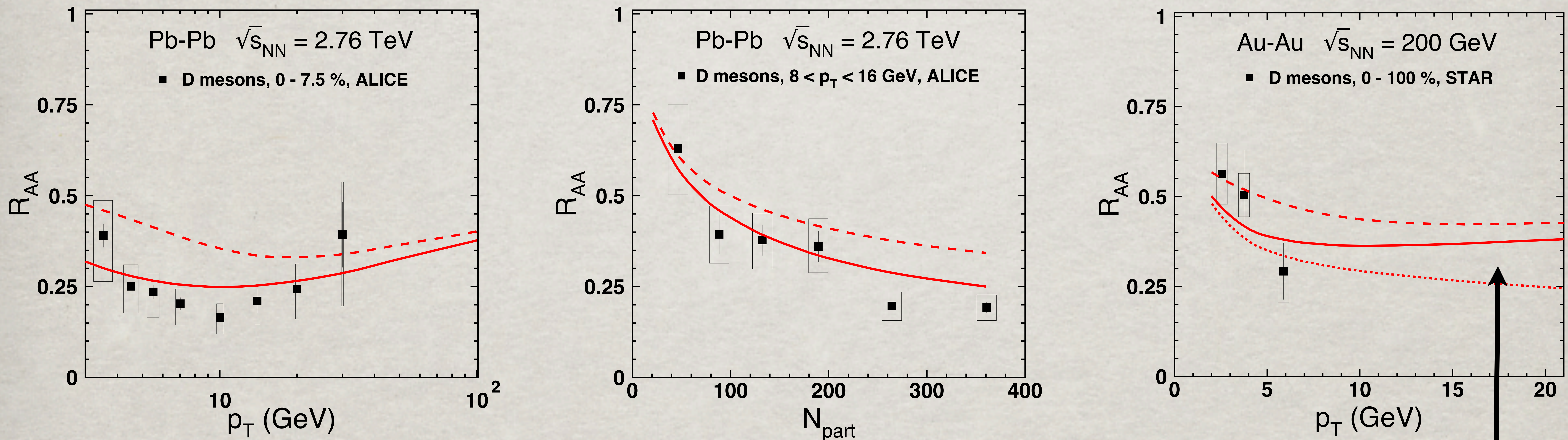
Different sources of time-dependent energy loss should be added up. Medium-induced energy loss is much smaller than the vacuum one, and should not produce a dramatic effect. They are particularly small for heavy flavors (Yu.Dokshitzer & D.Kharzeev (2001)





Results

c-quarks radiate in vacuum much more energy than b-quarks, while the effects of absorption of c-q and b-q dipoles in the medium are similar. Therefore D-mesons are suppressed in AA collisions more than B-mesons.



Initial state interaction effects, important at high-pT at RHIC, but not at LHC (so far).

J.Nemchik,I.Potashnikova,M.Johnson,I.Schmidt & B.K. PRC 72(2005)054606

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Summary

Fragmentation of high-pT heavy quarks expose nontrivial features.

- Heavy and light quarks produced in high-pT partonic collisions radiate differently. Heavy quarks regenerate their stripped-off color field much faster than light ones and radiate a significantly smaller fraction of the initial energy.
- This feature heavy-quark jets leads to a specific shape of the fragmentation functions. Differently from light flavors, the heavy quark fragmentation function strongly peaks at large fractional momentum z, i.e. the produced heavy-light meson, B or D, carry the main fraction of the jet momentum. This is a clear evidence of a short production time of a heavy-light mesons.
- On the contrary to the propagation of a small q-q dipole, which has survive due to color transparency, a q-Q dipole expands to a large size on a short time scale. Such a big dipole has a very low chance to survive intact in a hot medium. On the other hand, inelastic interactions with the medium, which lead to a dramatic suppression of leading light mesons, produce practically no effect on the leading q-Q mesons.
- Data for production of high-pT B and D mesons are explained in a parameter-free way.